5.4 Waterborne Radiological Consequences

> **POPULATION DOSE AND FUTURE POPULATION SIZE**
>
> *Population dose* is a summation of the doses received by individuals in an exposed population (unit of measure is *person-rem*). The population dose depends on the number of people at different locations. If the number of people increases in the future, the population dose estimate would also increase.

The following sections report the annual committed effective dose equivalent, expressed in millirem, to individuals living at three locations south of Yucca Mountain. These individuals are assumed to use contaminated groundwater and have lifestyle characteristics of the RMEI defined in 40 CFR 197.21. The RMEI is exposed to the high end of the range of potential dose distribution for the exposed population, called "reasonable maximum exposure" conditions. RMEI is a hypothetical person who meets the following criteria:

a) Lives at the location above where the highest concentration of radionuclides in the groundwater contamination plume crosses the boundary of the controlled area. The surface of the controlled area is defined as (40 CFR Part 197) the area, identified by passive institutional controls, that encompasses no more than 300 square kilometers. It must not extend farther south than 36º 40' 13.661" north latitude, in the predominant direction of groundwater flow, and no more than five kilometers from the repository footprint in any other direction

b) Has a diet and living style representative of the people who now reside in the Town of Amargosa Valley, Nevada. DOE must use projections based on surveys of the people residing in the Town of Amargosa Valley, Nevada, to determine their current diets and living styles and use the mean values of these factors in the assessments conducted for 40 CFR 197.20 and 197.25

c) Drinks 2 liters of water per day from wells drilled into the ground at the location specified in a).

While the RMEI is a regulatory definition for a specific location, impacts to individuals at two additional locations were evaluated using the lifestyle characteristics of the RMEI.

The analysis converted the annual committed effective dose equivalent, referred to as the annual individual dose, to the probability of contracting a fatal cancer (referred to as a latent cancer fatality) due to exposure to radioactive materials in the water. In addition, the analysis calculated population doses in person-rem for two different periods: for the 70-year lifetime at the time of the peak dose during the first 10,000 years after repository closure, and integrated over the first 10,000 years after repository closure. The analysis also converted the population dose to the expected number of latent cancer fatalities in the population. DOE based the analysis on the radionuclide inventories discussed in Section 5.1. However, the analysis included the entire carbon-14 inventory of the commercial spent nuclear fuel as a solid in the groundwater release models. Actually, 2 percent of the carbon-14 exists as a gas in the fuel (see Section 5.5). Thus, the groundwater models slightly overestimate (by 2 percent) the potential impacts from carbon-14.

The analysis studied potential consequences to individuals at three impact locations arising from waste mobilization and waterborne transport. A set of 300 model simulations were run using the GoldSim model (DIRS 155182-BSC 2001, all) for the RMEI location [about 18 kilometers (11 miles) from Yucca Mountain]. Each simulation used separate sets of sampled uncertainty parameters and generated an annual individual-dose profile for the 1 million years following repository closure. This set of simulations for the RMEI location, and some additional groundwater simulations (DIRS 154659-BSC 2001, Enclosure 3) provided the basis for calculating doses at 30 kilometers (19 miles) from the repository and at the discharge location near Franklin Lake Playa.

5.4.1 EXTENSION OF GROUNDWATER IMPACTS TO OTHER DISTANCES

The TSPA model estimates potential groundwater impacts for the RMEI location. This EIS provides groundwater impacts for two other important downgradient locations. These locations are 30 kilometers (19 miles), where most of the current population in the groundwater flow path is located, and 60 kilometers (37 miles), where the aquifer discharges to the surface (this location is also known as Franklin Lake Playa). The TSPA model used for the groundwater impacts at 18 kilometers (11 miles) is specifically designed for the RMEI location and is not directly usable to obtain reasonable estimates at farther distances. This is because conservative assumptions were embodied in the model, and the saturated zone transport model was designed primarily for the volcanic aquifer with characteristically very low mixing of waste in groundwater. Groundwater flow beyond the RMEI location occurs primarily in an alluvial medium with characteristically higher mixing, so plume concentrations would be reduced and a smaller quantity of radionuclides would be carried into the water usage wells.

Appendix I, Section I.4.5, details the development of distance scale factors using a three-dimensional analytical advection and dispersion transport model. Scaling factors were developed based on two criteria: attenuation of the peak concentrations in the plume and general increase in the cross-sectional area of the plume (that is, reduction of the average plume concentration). Two sets of factors were developed based on a large source size (characteristic of the repository footprint) and a small source size [10 meters by 10 meters (33 feet by 33 feet)]. The scaling factors were used to estimate *peak of the mean* and peak of the 95th-percentile annual individual doses and the groundwater concentrations at the two additional distances reported in Sections 5.4.2.1 and 5.4.2.2.

For the 10,000-year period of the nominal scenario, the dose would be attributable to the failure of a few waste packages. In this case, scaling factors based on a small size source were used. For the 1-million-year period, the release would be attributable to general releases over the whole repository area, so large source size scale factors were used. The factors based on the cross-section of the plume were chosen for the estimates. This was appropriate because the effect of water usage by the communities would be to cause significant mixing, and the more characteristic parameter would be the plume average concentration. Appendix I, Section I.4.5, includes scale factors for both approaches for comparison.

5.4.2 WATERBORNE RADIOLOGICAL RESULTS

This section discusses waterborne radiological consequences in relation to a higher-temperature repository operating mode and a lower-temperature operating mode. The individual and population dose calculations in this section were performed in a probabilistic manner using a volume of water necessary to operate 15 to 25 farms, representing a range of groundwater volumes from 1.1 million cubic meters to 4.2 million cubic meters (890 acre-feet to 3,400 acre-feet) with an average water demand of approximately 2.5 million cubic meters (2,000 acre-feet) per year. The final Nuclear Regulatory Commission regulations regarding a Yucca Mountain Repository state that the RMEI calculations should use an average water demand of 3,000 acre-feet [10 CFR 63.312(c)]. The 3.7-million-cubic-meter (3,000 acre-foot) water demand as specified by the Commission would result in dose estimates about two-thirds of the values in this section (DIRS 156743-Williams 2001, Section 6.3, pp. 12 and 13). The groundwater protection calculations in this section use 3,000 acre-feet water demand as called for in 40 CFR 197.31.

5.4.2.1 Waterborne Radiological Results for the Higher-Temperature Repository Operating Mode

The performance analysis indicated that for the first 10,000 years there would be very limited releases, attributable to early waste package failures due to waste package manufacturing defects, with very small radiological consequences (see Table 5-6). For the first 10,000 years after repository closure, the mean

Table 5-6. Impacts for an individual from groundwater releases of radionuclides during 10,000 years after repository closure for the higher-temperature repository operating mode.

Individual	Mean: Peak annual individual dose (millirem)	Mean: Time of peak (years)	Mean: Probability of an LCF[a]	95th-percentile: Peak annual individual dose (millirem)	95th-percentile: Time of peak (years)	95th-percentile: Probability of an LCF[a]
At RMEI location[b]	0.00002[c]	4,900	6×10^{-10}	0.0001[d]	4,900	4×10^{-9}
At 30 kilometers[e]	~0[f]	NC[g]	~0	~0[f]	NC	~0
At discharge location[h]	~0[f]	NC	~0	~0[f]	NC	~0

a. LCF = latent cancer fatality; incremental lifetime (70 years) risk of contracting a fatal cancer for individuals, assuming a risk of 0.0005 latent cancer per rem for members of the public (DIRS 101856-NCRP 1993, p. 31).
b. The RMEI location is approximately 18 kilometers (11 miles) downgradient from the repository. The maximum allowable peak of the mean annual individual dose for 10,000 years at this distance is 15 millirem.
c. Based on 300 simulations of total system performance, each using random samples of uncertain parameters.
d. Represents a value for which 285 out of the 300 simulations yielded a smaller value.
e. 30 kilometers = 19 miles.
f. Values would be lower than the small values computed for the RMEI location.
g. NC = not calculated (peak time would be greater than time given for the RMEI location).
h. 60 kilometers (37 miles) at Franklin Lake Playa.

WHY ARE THE MEAN IMPACTS SOMETIMES HIGHER THAN THE 95TH-PERCENTILE IMPACTS?

The *mean* impact is the arithmetic average of the 300 impact results from simulations of total-system performance. The mean is not the same as the 50th-percentile value (the 50th-percentile value is called the *median*) if the distribution is *skewed*.

The performance results reported in this EIS come from highly skewed distributions. In this context, *skewed* indicates that there are a few impact estimates that are much larger than the rest of the impacts. When a large value is added to a group of small values, the large value dominates the calculation of the mean. The simulations reported in this EIS have mean impacts that are occasionally above the 90th-percentile and occasionally above the 95th percentile.

peak would be 0.00002 millirem and the 95th-percentile peak would be 0.0001 millirem. The peaks would be even smaller at greater distances. This result was lower than the Environmental Protection Agency standard, which allows up to a 15-millirem annual committed effective dose equivalent during the first 10,000 years. In the remainder of this chapter, the "annual committed effective dose equivalent" is referred to as the "annual individual dose."

Table 5-7 lists the population consequences associated with the peak annual individual dose listed in Table 5-6. The population size was based on the projected population numbers for 2035 in Figure 3-25 in Chapter 3 of this EIS. For these calculations, the analysis assumed that no contaminated groundwater would reach populations in any regions to the north of Yucca Mountain. Therefore, populations in the sectors north of the due east and due west sectors in Figure 3-25 were not considered to be exposed.

- 47 people would be exposed at the RMEI location [includes sectors from 12 to 28 kilometers (7 to 17 miles)]

- 4,200 people would be exposed at about 30 kilometers (19 miles) downgradient from the potential repository [includes sectors from 28 to 44 kilometers (17 to 27 miles)]

Table 5-7. Population impacts from groundwater releases of radionuclides during 10,000 years after repository closure for the higher-temperature repository operating mode.

Impact	Mean		95th-percentile	
	Population dose (person-rem)	Population LCF[a]	Population dose (person-rem)	Population LCF[c]
Peak 70-year lifetime	0.006	0.000003	0.04	0.00002
Integrated over 10,000 years	0.5	0.0002	0.6	0.0003

a. LCF = latent cancer fatality; expected number of cancer fatalities for populations, assuming a risk of 0.0005 latent cancer per rem for members of the public (DIRS 101856-NCRP 1993, p. 31).

- 69,500 people would be exposed at the discharge location about 60 kilometers (37 miles) downgradient from the potential repository [includes sectors from 44 to 80 kilometers (27 to 50 miles)]

Thus, approximately 74,000 people would be exposed to contaminated groundwater. This stylized population dose analysis assumed that people would continue to live in the locations being used at present. This assumption is consistent with the recommendation made by the National Academy of Sciences (DIRS 100018-National Research Council 1995, all) because it is impossible to make accurate predictions of lifestyles and residence locations far into the future.

The values in Table 5-7 include a scaling factor for water use. The performance assessment transport model calculated the annual individual dose assuming the radionuclides dissolved in water that flowed through the unsaturated zone of Yucca Mountain would mix in an average of 2.4 million cubic meters (1,940 acre feet) (DIRS 155950-BSC 2001, p. 13-42) per year in the saturated zone aquifer. This compares to an annual water use in the Amargosa Valley of about 17.1 million cubic meters (13,900 acre-feet) (DIRS 155950-BSC 2001, p. 13-42). The analysis diluted the concentration of the nuclides in the 2.4 million cubic meters of water throughout the 17.1 million cubic meters of water before calculating the population dose.

The small consequences listed in Tables 5-6 and 5-7 would result from the durability of the waste packages; most of which would remain intact significantly longer than 10,000 years. The outer layer of the waste package would be subject to a very low average corrosion rate, but there is a high degree of uncertainty in the value of that average corrosion rate. Model simulations incorporated a small number of waste package failures within 10,000 years due to manufacturing defects; the dose results in Tables 5-6 and 5-7 during this period would result directly from these early failures.

The radionuclides that would contribute the most to individual dose in 10,000 years would be technetium-99, carbon-14 dissolved in groundwater, and iodine-129. For example, the mean consequence at 18 kilometers (11 miles) has technetium-99 contributing 77 percent of the total annual individual dose rate, carbon-14 contributing 16 percent, and iodine-129 contributing 7 percent. While the atmospheric analysis in this EIS assumed that 2 percent of the carbon-14 migrated as gas in the form of carbon dioxide (see Section 5.5 for more details), the groundwater modeling for this waterborne radiological consequences analysis conservatively assumed that all of the carbon-14 migrated in the groundwater.

Table 5-8 lists impacts for the post-10,000-year period. The table lists the mean and 95th-percentile peak annual individual dose and the times of the associated peaks at three locations. The mean and 95th-percentile annual individual doses during 1 million years following repository closure are shown in Figure 5-4. The multiple peaks occurring 200,000 years or more after repository closure are driven by transitions between climate states.

Table 5-8. Impacts for an individual from groundwater releases of radionuclides during 1 million years after repository closure for the higher-temperature repository operating mode.

Individual	Mean: Peak annual individual dose (millirem)	Mean: Time of peak (years)	95th-percentile: Peak annual individual dose (millirem)	95th-percentile: Time of peak (years)
At RMEI location[a]	150[b]	480,000	620[c]	410,000
At 30 kilometers[d]	100[e]	NC[f]	420[e]	NC
At discharge location[g]	59[e]	NC	240[e]	NC

a. The RMEI location is approximately 18 kilometers (11 miles) downgradient from the repository.
b. Based on 300 simulations of total system performance, each using random samples of uncertain parameters.
c. Represents a value for which 285 out of the 300 simulations yielded a smaller value.
d. 30 kilometers = 19 miles.
e. Estimated using scale factors as described in Section 5.4.1.
f. NC = not calculated (peak time would be greater than time given for the RMEI location).
g. 60 kilometers (37 miles) at Franklin Lake Playa.

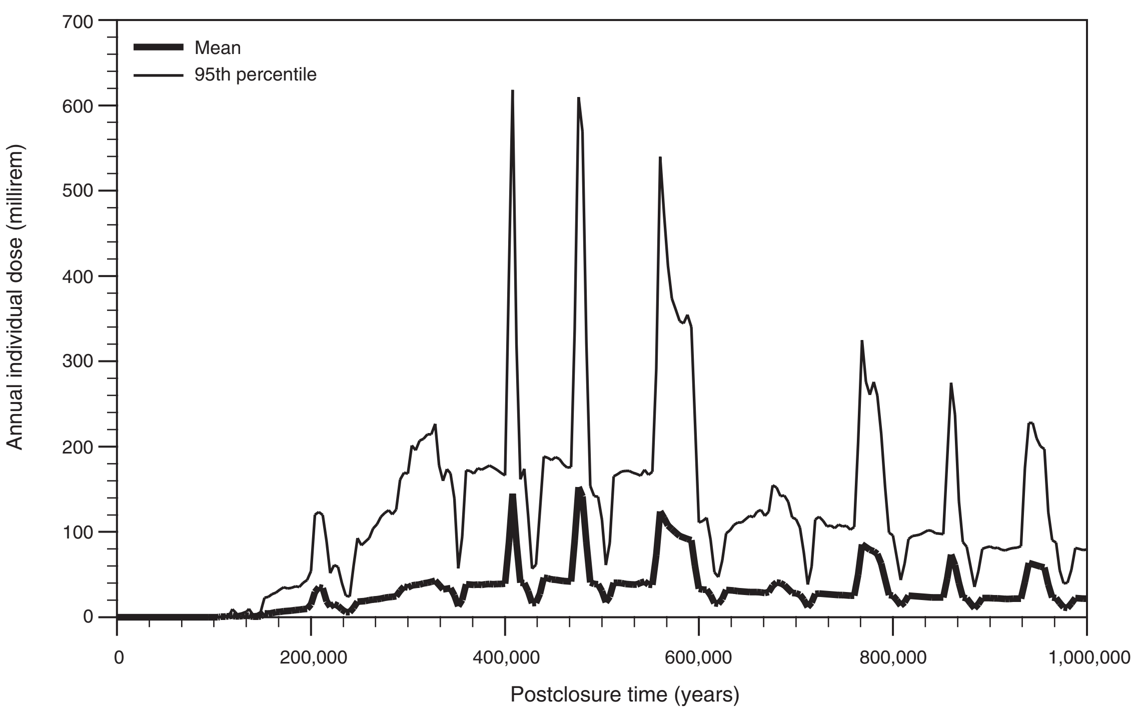

Figure 5-4. Mean and 95th-percentile (based on 300 simulations of total system performance, each using random samples of uncertain parameters) annual individual dose at the RMEI location during 1 million years after repository closure for the nominal scenario under the higher-temperature repository operating mode.

The simulations were ended after 1 million years largely because further radioactive decay would continue to decrease the annual individual dose even for very long-lived radionuclides. The peak annual individual dose usually coincided with the occurrence of a wetter climate period.

The radionuclides that would contribute the most to the peak annual individual dose in 1 million years would be neptunium-237 and plutonium-242. The mean peak annual individual dose at the RMEI location would have neptunium-237 contributing 61 percent of the total annual individual dose, plutonium-242 contributing 13 percent, actinium-227 contributing 5 percent, thorium-229 and uranium-234 each contributing 3 percent, and uranium-233, lead-210, and radium-226 each contributing 2 percent. The plutonium isotopes contributing to dose would be due to colloidal transport of plutonium, not transport of plutonium as a dissolved element in groundwater.

With respect to the groundwater protection standards in 40 CFR 197.30, both the mean and 95th-percentile estimated levels during the 10,000-year regulatory period would be hundreds of thousands of times less than the regulatory limits (see Table 5-9).

Table 5-9. Comparison of nominal scenario long-term consequences at the RMEI location[a] to groundwater protection standards during 10,000 years following repository closure for the higher-temperature repository operating mode.

Radionuclide or type of radiation emitted	EPA limit[b]	Mean peak[c]	95th-percentile peak[d]
Combined radium-226 and radium-228[e] (picocuries per liter)	5	1.0 (1×10^{-11})[f]	1.0 (2×10^{-11})[f]
Gross alpha activity (including radium-226 but excluding radon and uranium)[e] (picocuries per liter)	15	0.4 (2×10^{-8})[f]	0.4 (1×10^{-8})[f]
Combined beta- and photon-emitting radionuclides,[g] millirem per year to the whole body or any organ,[h] based on drinking 2 liters[i] of water per day from the representative volume	4	2×10^{-5}	1×10^{-4}

a. The RMEI location is approximately 18 kilometers (11 miles) downgradient from the repository.
b. Environmental Protection Agency limits at 40 CFR 197.30.
c. Based on 300 simulations of total system performance, each using random samples of uncertain parameters.
d. Represents a value for which 285 out of the 300 simulations yielded a smaller value.
e. Includes natural background radiation.
f. Value in parentheses is the incremental increase over background radiation that would be attributable to the potential repository.
g. Does not include natural background radiation.
h. This represents a bounding (overestimate) of the maximum dose to any organ because the different radionuclides would affect different organs preferentially.
i. 2 liters = 0.53 gallon.

5.4.2.2 Waterborne Radiological Results for the Lower-Temperature Repository Operating Mode

DOE conducted performance studies for the lower-temperature repository operating mode. This section discusses groundwater impacts for the lower-temperature operating mode. The performance analysis indicated that for the first 10,000 years there would be very limited releases, attributable to early waste package failures due to waste package manufacturing defects, with very small radiological consequences (see Table 5-10). For the first 10,000 years after repository closure, the mean peak would be 0.00001 millirem and the 95th-percentile peak would be 0.0001 millirem. The peaks would be even smaller at greater distances. This result was compared to the EPA standard, which allows up to a 15-millirem annual individual dose during the first 10,000 years.

Table 5-11 lists the population consequences associated with the peak annual individual dose listed in Table 5-10. The population size was based on the population numbers projected for the year 2035 in Figure 3-25 in Chapter 3 of this EIS. For these calculations, the analysis assumed that no contaminated groundwater would reach populations in any regions to the north of Yucca Mountain. Therefore, populations in the sectors north of the due east and due west sectors in Figure 3-25 were not considered to be exposed.

Table 5-10. Impacts for an individual from groundwater releases of radionuclides during 10,000 years after repository closure for the lower-temperature repository operating mode.

	Mean			95th-percentile		
Individual	Peak annual individual dose (millirem)	Time of peak (years)	Probability of an LCF[a]	Peak annual individual dose (millirem)	Time of peak (years)	Probability of an LCF[a]
At RMEI location[b]	0.00001[c]	3,400	4×10^{-10}	0.0001[d]	5,000	3×10^{-9}
At 30 kilometers[e]	~0[f]	NC[g]	~0	~0[f]	NC	~0
At discharge location[h]	~0[f]	NC	~0	~0[f]	NC	~0

a. LCF = latent cancer fatality; incremental lifetime (70 years) risk of contracting a fatal cancer for individuals, assuming a risk of 0.0005 latent cancer per rem for members of the public (DIRS 101856-NCRP 1993, p. 31).
b. The RMEI location is approximately 18 kilometers (11 miles) downgradient from the repository. The maximum allowable peak of the mean annual individual dose for 10,000 years at this location is 15 millirem.
c. Based on 300 simulations of total system performance, each using random samples of uncertain parameters.
d. Represents a value for which 285 out of the 300 simulations yielded a smaller value.
e. 30 kilometers = 19 miles.
f. Values would be lower than the small values computed for the RMEI location.
g. NC = not calculated (peak time would be greater than time given for the RMEI location).
h. 60 kilometers (37 miles) at Franklin Lake Playa.

Table 5-11. Population impacts from groundwater releases of radionuclides during 10,000 years after repository closure for the lower-temperature repository operating mode.

	Mean		95th-percentile	
Impact	Population dose (person-rem)	Population LCF[a]	Population dose (person-rem)	Population LCF[c]
Peak 70-year lifetime	0.004	0.000002	0.03	0.00002
Integrated over 10,000 years	0.3	0.0002	0.4	0.0002

a. LCF = latent cancer fatality; expected number of cancer fatalities for populations, assuming a risk of 0.0005 latent cancer per rem for members of the public (DIRS 101856-NCRP 1993, p. 31).

- 47 people would be exposed at the RMEI location (includes sectors from 12 to 28 kilometers)
- 4,200 people would be exposed at about 30 kilometers (19 miles) downgradient from the potential repository (includes sectors from 28 to 44 kilometers)
- 69,500 people would be exposed at the discharge location about 60 kilometers (37 miles) downgradient from the potential repository (includes sectors from 44 to 80 kilometers)

Thus, approximately 74,000 people would be exposed to contaminated groundwater. This stylized population dose analysis assumed that people would continue to live in the locations being used at present. This assumption is consistent with the recommendation made by the National Academy of Sciences (DIRS 100018-National Research Council 1995, all) because it is impossible to make accurate predictions of lifestyles and residence locations far into the future.

The values in Table 5-11 include a scaling factor for water use. The performance assessment transport model calculated the annual individual dose assuming the radionuclides dissolved in water that flowed through the unsaturated zone of Yucca Mountain would mix in an average of 2.4 million cubic meters (1,940 acre-feet) (DIRS 155950-BSC 2001, p. 13-42) per year in the saturated zone aquifer. This compares to an annual water use in the Amargosa Valley of about 17.1 million cubic meters (13,900 acre-feet) (DIRS 155950-BSC 2001, p. 13-42). The analysis diluted the concentration of the nuclides in the 2.4 million cubic meters of water throughout the 17.1 million cubic meters of water before calculating the population dose.

The small consequences listed in Tables 5-10 and 5-11 would result from the durability of the waste packages; most of which would remain intact significantly longer than 10,000 years. The outer layer of the waste package would be subject to a very low average corrosion rate, but there is a high degree of uncertainty in the value of that average corrosion rate. Model simulations incorporated a small number of waste package failures within 10,000 years due to manufacturing defects; the dose results in Table 5-10 and 5-11 during this period would result directly from these early failures.

The radionuclides that would contribute the most to individual dose in 10,000 years would be technetium-99, carbon-14 dissolved in groundwater, and iodine-129. For example, the mean consequence at 18 kilometers (11 miles) has technetium-99 contributing 63 percent of the total individual dose rate, carbon-14 contributing 25 percent, and iodine-129 contributing 10 percent. While the atmospheric analysis in this EIS assumed that 2 percent of the carbon-14 migrated as gas in the form of carbon dioxide (see Section 5.5 for more details), the groundwater modeling for this waterborne radiological consequences analysis conservatively assumed that all of the carbon-14 migrated in the groundwater.

Table 5-12 lists impacts for the post-10,000-year period as peak annual doses. The table lists the mean and 95th-percentile peak annual individual dose and the times of the associated peaks at three locations. The mean and 95th-percentile annual individual doses during 1 million years following repository closure are shown in Figure 5-5. The multiple peaks occurring 200,000 years or more after repository closure are driven by transitions between climate states.

Table 5-12. Impacts for an individual from groundwater releases of radionuclides during 1 million years after repository closure for the lower-temperature repository operating mode.

	Mean		95th-percentile	
Individual	Peak annual individual dose (millirem)	Time of peak (years)	Peak annual individual dose (millirem)	Time of peak (years)
At RMEI location[a]	120[b]	480,000	510[c]	410,000
At 30 kilometers[d]	83[e]	NC[f]	350[e]	NC
At discharge location[g]	48[e]	NC	240[e]	NC

a. The RMEI location is approximately 18 kilometers (11 miles) downgradient from the repository.
b. Based on 300 simulations of total system performance, each using random samples of uncertain parameters.
c. Represents a value for which 285 out of the 300 simulations yielded a smaller value.
d. 30 kilometers = 19 miles.
e. Estimated using scale factors as described in Section 5.4.1.
f. NC = not calculated (peak time would be greater than time given for the RMEI location).
g. 60 kilometers (37 miles) at Franklin Lake Playa.

The simulations were ended after 1 million years largely because further radioactive decay would continue to decrease annual individual dose even for very long-lived radionuclides. The peak annual individual dose usually coincided with the occurrence of a wetter climate period.

The radionuclides that would contribute the most to the peak annual individual dose in 1 million years would be neptunium-237 and plutonium-242. The mean peak dose at 18 kilometers (11 miles) would have neptunium-237 contributing 63 percent of the total individual dose rate, plutonium-242 contributing 12 percent, actinium-227 contributing 5 percent, thorium-229 and uranium-234 each contributing 3 percent, and uranium-233, lead-210, and radium-226 each contributing 2 percent. The plutonium isotopes contributing to dose would be due to colloidal transport of plutonium, not transport of plutonium as a dissolved element in groundwater.

With respect to the groundwater protection standards in 40 CFR 197.30, both the mean and 95th-percentile estimated levels during the 10,000-year regulatory period would be hundreds of thousands of times less than the regulatory limits (see Table 5-13).

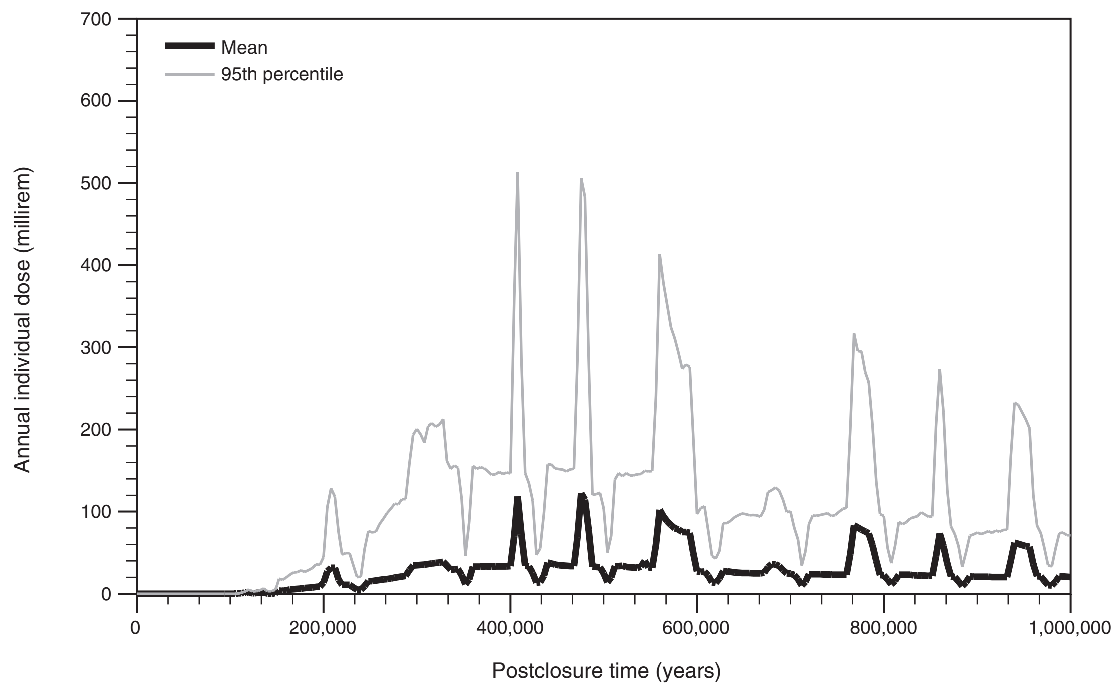

Figure 5-5. Mean and 95th-percentile (based on 300 simulations of total system performance, each using random samples of uncertain parameters) annual individual dose at the RMEI location during 1 million years after repository closure for the nominal scenario under the lower-temperature repository operating mode.

Table 5-13. Comparison of nominal scenario long-term consequences at the RMEI location[a] to groundwater protection standards during 10,000 years following repository closure for the lower-temperature repository operating mode.

Radionuclide or type of radiation emitted	EPA limit[b]	Mean peak[c]	95^{th}-percentile peak[d]
Combined radium-226 and radium-228[e] (picocuries per year)	5	1 (2×10^{-12})[f]	1 (1×10^{-11})[f]
Gross alpha activity (including radium-226 but excluding radon and uranium)[e] (picocuries per year)	15	0.4 (3×10^{-8})[f]	0.4 (2×10^{-8})[f]
Combined beta- and photon-emitting radionuclides,[g] millirem per year to the whole body or any organ,[h] based on drinking 2 liters[i] of water per day from the representative volume	4	1×10^{-5}	7×10^{-5}

a. The RMEI location is approximately 18 kilometers (11 miles) downgradient from the repository.
b. Environmental Protection Agency limits set forth in 40 CFR 197.30.
c. Based on 300 simulations of total system performance, each using random samples of uncertain parameters.
d. Represents a value for which 285 out of the 300 simulations yielded a smaller value.
e. Includes natural background radiation.
f. Value in parentheses is the incremental increase over background radiation that would be attributable to the potential repository.
g. Does not include natural background radiation.
h. This represents a bounding (overestimate) of the maximum dose to any organ because the different radionuclides would affect different organs preferentially.
i. 2 liters = 0.53 gallon.

5.4.2.3 Alternative Dosimetry Methods

The long-term postclosure groundwater impacts are estimated using ICRP-30 (DIRS 110386-ICRP 1979, all; DIRS 110351-ICRP 1980, all; DIRS 110352-ICRP 1981, all) domestic methods. It has been suggested by an international peer review that the more recent ICRP-72 methods (DIRS 152446-ICRP 1996, all), as are used internationally for such estimates, would be more appropriate. Sensitivity studies indicate the peak dose estimates would be about a factor of 4 lower if the ICRP-72 analytical methods were applied (DIRS 157151-BSC 2001, Appendix L. pp. L-31 to L-33).

5.5 Atmospheric Radiological Consequences

After DOE closed the repository, there would be limited potential for releases to the atmosphere because the waste would be isolated far below the ground surface. Still, the rock is porous and does allow gas to flow, so the analysis must consider possible airborne releases. The only radionuclide in the analysis after screening with a potential for gas transport is carbon-14 in the form of carbon dioxide. Iodine-129 can exist in a gas phase, but DOE expects it would dissolve in the groundwater rather than migrate as a gas. The solubility of iodine-129 is a great deal higher than that of carbon dioxide, and the water is already saturated in carbon dioxide because of interaction with carbonate rocks. After the carbon-14 escaped as carbon dioxide from the waste package, it would flow through the rock. About 2 percent of the carbon-14 in commercial spent nuclear fuel is in a gas phase in the space (or gap) between the fuel and the cladding around the fuel (DIRS 103446-Oversby 1987, p. 92). The atmospheric model used a gas-phase inventory of 0.122 curie of carbon-14 per waste package of commercial spent nuclear fuel at the time of emplacement. The atmospheric model estimated human health impacts for the population in the 80-kilometer (50-mile) region surrounding the repository.

In addition, DOE considered the possible impacts from the release of radon from the repository. Radon is a decay product of uranium and would be generated for as long as any uranium remained in the repository. Based on gas flow studies, DOE believes that radon would decay before it reached the ground surface. Appendix I, Section I.7.3, contains a more detailed screening discussion.

5.5.1 SOURCE TERM

The calculation of regional doses used an estimate of the annual release rate of carbon-14. The analysis based the carbon-14 release rate on the estimated time line of waste package container failures for the higher-temperature repository operating mode nominal scenario. If the same analysis were performed using waste package failures for the lower-temperature operating mode, the results would be nearly the same with slightly lower impacts. The expected number of commercial spent nuclear fuel waste package failures as a function of time was used to estimate the carbon-14 release rates after repository closure. The amount of material released from each package as a function of time was reduced to account for radioactive decay. As for the waterborne releases described in Section 5.4.1, credit was taken for the intact zirconium alloy cladding (on approximately 99 percent by volume of the spent nuclear fuel at emplacement) delaying the release of gas-phase carbon-14 (DIRS 153849-DOE 2001, p. 3-7). The remaining 1 percent by volume of the spent nuclear fuel either would have stainless-steel cladding (which degrades much more quickly than zirconium alloy) or would already have failed in the reactor. Thus, gas-phase releases from this fuel would have occurred before it was shipped to the repository. The maximum annual-release rate would occur about 1,700 years after repository closure, and the estimated maximum release rate would be 3.3 microcuries per year of carbon-14.

5.5.2 ATMOSPHERIC CONSEQUENCES TO THE LOCAL POPULATION

DOE used the *GENII* program (DIRS 100953-Napier et al. 1988, all) to model the atmospheric transport and human uptake of the released carbon-14 for the 80-kilometer (50-mile) population dose calculation.

Doses to the regional population around Yucca Mountain from carbon-14 releases were estimated using the population distribution shown in Chapter 3, Figure 3-25, which indicates that 76,000 people would live in the region surrounding Yucca Mountain in 2035. The computation also used current (1993 to 1996) annual average meteorology (see Appendix I, Table I-33). GENII calculated a dose factor of 4.6×10^{-9} person-rem per microcurie per year of release. For a 3.3-microcurie-per-year release, this corresponds to a maximum 80-kilometer annual population dose of 1.5×10^{-8} person-rem. This dose corresponds to 7.5×10^{-12} latent cancer fatality in the regional population of 76,000 persons during each year at the maximum carbon-14 release rate. This annual population radiological dose corresponds to a 70-year lifetime radiological population dose of 1.1×10^{-6} person-rem, which corresponds to 5.3×10^{-10} latent cancer fatality during the 70-year period of the maximum release.

5.5.3 ATMOSPHERIC CONSEQUENCES TO AN INDIVIDUAL

For a constant-sized population living only at the locations in the population distribution shown in Chapter 3, Figure 3-25, a maximally exposed individual for airborne releases would reside 24 kilometers (15 miles) south of the repository. The location for maximum dose is dependent on wind speed and wind direction, and is only considered for those locations where people currently reside (it was not a predetermined location). An individual radiological dose factor of 5.6×10^{-14} rem per microcurie per year of release was calculated using the GENII code for this location. For a 3.3-microcurie-per-year maximum release rate, the individual maximum radiological dose rate would be 1.8×10^{-13} rem per year, corresponding to a 9.2×10^{-17} probability of a latent cancer fatality. The 70-year lifetime dose would be 1.3×10^{-11} rem, representing a 6.4×10^{-15} probability of a latent cancer fatality.

5.6 Consequences from Chemically Toxic Materials

A number of nonradioactive materials that DOE would place in the repository will degrade over time into materials that are hazardous to human health at high concentrations in water. This section examines the consequences to individuals in the Amargosa Desert from releases of these nonradioactive materials.

Appendix I, Section I.3 discusses the inventory of chemically toxic materials that would be emplaced in the repository under the Proposed Action by element. Based on this inventory, a screening analysis (described in Appendix I, Section I.6.1) identified which of the chemically toxic materials could pose a potential risk to human health. Chromium, molybdenum, nickel, and vanadium were identified as posing such a potential risk, and these elements were further evaluated in a bounding consequence analysis, as described in Appendix I, Section I.6.2. This analysis makes the conservative assumption that all chromium dissolves in hexavalent form.

It should also be noted that all of the chromium, molybdenum, nickel, and vanadium considered are elements contained in the metals used to package the waste and support the packages. None of the materials inside the waste packages were considered because, except for about three packages, all packages would last for more than 50,000 years.

Table 5-14 summarizes the results of the bounding analysis. In some cases a Maximum Contaminant Level or Maximum Contaminant Level Goal was available for comparison to the calculated concentration. In other cases, only an Oral Reference Dose was available. The Oral Reference Dose can be compared to the intake that would result for a 70-kilogram (154-pound) person drinking 2 liters (0.53 gallon) of water per day.

The bounding consequence analysis estimated that the maximum peak concentration of chromium in groundwater used at exposure locations would be 0.01 milligram per liter. There are two measures for comparing human health effects for chromium. When the Environmental Protection Agency established its Maximum Contaminant Level Goals, it considered safe levels of contaminants in drinking water and

Table 5-14. Consequences from waterborne chemically toxic materials release during 10,000 years after repository closure estimated using a bounding calculation.

Material	Concentration in well water (milligram per liter)	Maximum Contaminant Level Goal[a] (milligram per liter)	Intake rate for a 70-kilogram person (milligram per kilogram per day)	Oral Reference Dose (milligram per kilogram per day)
Chromium (VI)	0.01	0.1	0.0004	0.005[b]
Molybdenum	0.009	NA[c]	0.0003	0.005[d]
Nickel	0.04	NA	0.001	0.02[e]
Vanadium	0.0002	NA	0.000006	0.007[f]

a. 40 CFR 141.51.
b. DIRS 148224-EPA (1999, all).
c. NA = not available.
d. DIRS 148228-EPA (1999, all).
e. DIRS 148229-EPA (1999, all).
f. DIRS 103705-EPA (1997, all).

the ability to achieve these levels with the best available technology. The Maximum Contaminant Level Goal for chromium is 0.1 milligram per liter (40 CFR 141.51). The bounding concentration is well below the Maximum Contaminant Level Goal for chromium (about one-tenth of this limit). The other measure for comparison is the reference dose factor for chromium, which is an intake of 0.0004 milligram of chromium per kilogram of body mass per day (DIRS 148224-EPA 1999, all). The reference dose factor represents a level of intake that has no adverse effect on humans. It can be converted to a threshold concentration level for drinking water. The conversion yields essentially the same concentration for the reference dose factor as the Maximum Contaminant Level Goal. At present, the bounding estimate of groundwater concentration of hexavalent chromium cannot be expressed in terms of human health effects (for example, latent cancer fatalities). The carcinogenicity of hexavalent chromium by the oral route of exposure has not been determined because of a lack of sufficient epidemiological or toxicological data (DIRS 148224-EPA 1999, all; DIRS 101825-EPA 1998, p. 48).

The estimated bounding concentration of molybdenum in groundwater used at exposure locations would be 0.009 milligram per liter. There is no Maximum Contaminant Level Goal for molybdenum but intake can be compared to the Oral Reference Dose. The intake rate from drinking 2 liters (0.53 gallon) per day of contaminated water by a 70-kilogram (154-pound) person would be 0.0003 milligram per kilogram per day. This is well below the Oral Reference Dose of 0.005 milligram per kilogram per day (DIRS 148228-EPA 1999, all).

The estimated bounding concentration of nickel in groundwater used at exposure locations would be 0.04 milligram per kilogram. There is no Maximum Contaminant Level Goal available for nickel but intake can be compared against the Oral Reference Dose. The intake rate from drinking 2 liters (0.53 gallon) per day of contaminated water by a 70-kilogram (154-pound) person would be 0.001 milligram per kilogram per day. This is well below the Oral Reference Dose of 0.02 milligram per kilogram per day.

The estimated bounding concentration of vanadium in groundwater used at exposure locations would be 0.0002 milligram per liter. There is no Maximum Contaminant Level Goal available for vanadium, but intake can be compared to the Oral Reference Dose. The intake rate from drinking 2 liters (0.53 gallon) per day of contaminated water by a 70-kilogram (154-pound) person would be 0.000006 milligram per kilogram per day. This is well below the Oral Reference Dose of 0.007 milligram per kilogram per day.

Because the estimated bounding concentrations of chromium, molybdenum, nickel and vanadium in well water would be below the Maximum Contaminant Level Goal or yield intakes well below the Oral Reference Dose, there is no further need to refine the calculation to account for physical processes that would limit mobilization of those materials or delay and dilute them during transport in the geosphere.

5.7 Consequences from Disruptive Events

The postclosure performance estimates discussed in Sections 5.4, 5.5, and 5.6 include the possible effects of changing climate and seismic events but do not address other events that could physically disturb the repository. In general, disruptive events have identifiable starting and ending times, in contrast to continuous processes such as corrosion. The disruptive events examined in this section are an *inadvertent intrusion* into the repository by a drilling crew and basaltic igneous (volcanic) activity.

5.7.1 HUMAN INTRUSION SCENARIO

DOE examined the consequences of a human intrusion scenario involving inadvertent drilling.

The human intrusion scenario analyzed in this EIS is consistent with the requirements of 40 CFR Part 197. The stylized human intrusion scenario is summarized as follows:

- The human intrusion would occur 30,000 years after permanent repository closure when there was enough degradation in waste packages that the driller might not detect the penetration.
- The intrusion would result in a single, nearly vertical borehole that penetrated a waste package and extended down to the saturated zone.
- Current practices for resource exploration would be used to establish properties (e.g., borehole diameter, drilling fluid composition).
- The borehole would not be adequately sealed and would permit infiltrating water and natural degradation processes to modify the borehole gradually.
- Only releases through the borehole to the saturated zone were considered; hazards to the drillers or to the public from material brought to the surface by the assumed intrusion were not included.

The human intrusion results were calculated probabilistically, analogous to the nominal scenario calculations for waterborne radioactive material releases. The calculations were carried out for the higher-temperature repository operating mode. For this stylized intrusion scenario, there would be no difference for the lower-temperature operating mode because exactly one waste package is intersected for both operating modes and its inventory is moved to the saturated zone where further transport does not depend on repository operating mode. Figure 5-6 shows the mean and 95th-percentile annual individual dose for 1 million years resulting from a human intrusion 30,000 years after repository closure for the set of 300 simulations. The values in Figure 5-6 represent the dose from a single waste package, and are not combined with releases for other waste packages that would fail due to other processes. The peak of the mean annual individual dose from human intrusion would be 0.002 millirem, occurring a short time after 100,000 years after repository closure. These results indicate that the repository would be sufficiently robust and resilient to limit releases caused by human intrusion to values well below the 15-millirem annual individual dose standard.

The analysis did not combine the results of the disruptive igneous event scenario with the results of the human intrusion scenario. However, combined results can be approximated by adding the results of the human intrusion analysis to that of the disruptive igneous event scenario, which would result in a total combined maximum dose. Based on the results presented in this section and Section 5.7.2, the highest mean annual individual dose that would result from an intrusion would be less than one-tenth of the radiological dose from a disruptive igneous event.

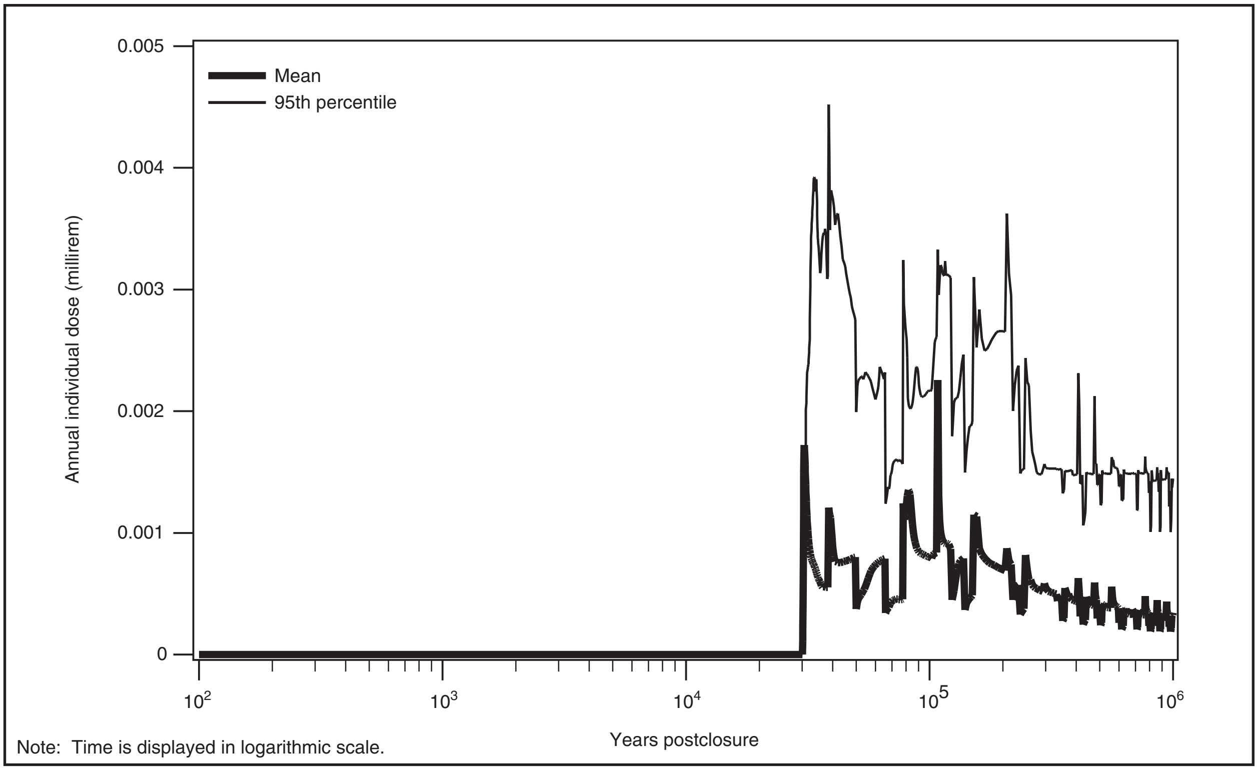

Figure 5-6. Mean and 95th-percentile annual individual dose at the RMEI location resulting from human intrusion 30,000 years after repository closure under the higher-temperature repository operating mode.

A sensitivity study where the human intrusion occurs at 100 years after repository closure has also been conducted (DIRS 157307-BSC 2001, Enclosure 1).

5.7.2 IGNEOUS ACTIVITY SCENARIO

The analysis of igneous activity utilized a model for volcanic eruptions that would intersect drifts and bring waste to the surface, and a model for igneous intrusions that would damage waste packages, thereby exposing radionuclides to groundwater for transport.

5.7.2.1 Volcanic Eruption Events

The conceptualization of a volcanic eruption at Yucca Mountain envisioned an igneous dike that would rise through the Earth's crust and intersect one or more repository drifts. An eruptive conduit could form somewhere along the dike as it neared the land surface, feeding a volcano at the surface. Waste packages in the direct path of the conduit would be destroyed, and the waste in those packages would subsequently be entrained in the eruption. Volcanic ash would be contaminated, erupted, and transported by wind. Ash would settle out of the plume as it was transported downwind, resulting in an ash layer on the land surface. Members of the public would then receive a radiation dose from exposure pathways associated with the contaminated ash layer.

Model development included the selection of conservative assumptions about the event, selection of input parameter distributions characterizing important physical properties of the system, and use of a computational model to calculate entrainment of waste in the erupting ash. Each intrusive event (a swarm of one or more dikes) was assumed to generate one or more volcanoes somewhere along its length, but eruptions would not need to occur within the repository footprint. Approximately 77 percent of intrusive events that intersected the repository would be associated with one or more surface eruptions within the repository footprint. The number of eruptive conduits (volcanoes) is independent of the number of dikes in a swarm. Characteristics of the eruption such as eruptive power, style (violent versus normal), velocity, duration, column height, and total volume of erupted material, are included in the analysis.

5.7.2.2 Groundwater Transport of Radionuclides Following Igneous Intrusion Event

The conceptualization of radionuclide release and transport away from waste packages damaged by an igneous intrusion that intersected the repository is similar to the nominal model for radionuclide release and transport (discussed in Section 5.4), but was modified to include the intrusion. The igneous intrusion groundwater transport model includes a set of input parameters to define a modified source term for use in the nominal scenario flow and transport model. There are three main components to the model: the behavior of the waste packages and other engineered barrier system elements damaged because of their proximity to an igneous intrusion; groundwater flow and radionuclide transport away from the waste packages; and calculation of the number of waste packages damaged as a result of the igneous intrusion.

The analysis assumed that waste packages close to the point of intrusion would be so damaged that they would provide no further protection for the waste. Actual conditions would be uncertain, and damage probably would range from moderate to extensive. Nominal models for radionuclide mobilization and transport were used even though conditions would change in the drift following intrusion. All waste in the most severely damaged packages would be immediately available for transport in the unsaturated zone, depending on solubility limits and the availability of water, which was determined using the seepage model for nominal performance. The thermal, chemical, and mechanical effects of the intrusion on the drift environment were neglected. No credit was taken for water diversion by the remnants of the drip shield or waste package, and cladding was assumed to be fully degraded. Actual thermal, chemical, hydrological, and mechanical conditions in the drift following igneous intrusion are unknown, although conservatively assuming that the engineered barriers would have completely failed is sufficient to compensate for the uncertainty associated with conditions in the drift.

5.7.2.3 Results for Igneous Activity Scenario

The approach taken to calculate doses resulting from the igneous activity scenario is consistent with the probabilistic methodology described in Nuclear Regulatory Commission guidance (DIRS 103760-NRC 1998, all; DIRS 119693-Reamer 1999; all). Scenario consequences are multiplied ("weighted") by the probability of occurrence of the scenario to yield an appropriate estimate of the overall risk posed by low-probability events. The probability of igneous activity is extremely low (the mean annual probability is 1.6×10^{-8}), and the probability of more than one igneous disruption occurring during the next 100,000 years is far below the level of concern. Therefore, the analysis considered only a single igneous eruption within the repository during the next 100,000 years, occurring with a mean 100,000-year probability of 1.6×10^{-3}. The year in which that eruption could occur is uncertain; therefore, the igneous eruption scenario was evaluated as if it were many different eruptive scenarios, each occurring in a different 25-year time interval, and each occurring with a probability 25 times that of the annual probability. The average dose resulting from igneous disruption was determined by calculating doses resulting from igneous events in each 25-year period, multiplying by the probability (mean 25-year probability of 4.0×10^{-7}), and adding the doses from each *disruptive event*. For computational efficiency, igneous intrusions that would not result in a surface eruption were simulated using a simpler approach in which the time of intrusion was sampled randomly from the 100,000-year period, and the probability associated with each simulation is the full 100,000-year probability of 1.6×10^{-3}. Probability-weighted doses from both eruptive and intrusive events were added together to give the total dose from igneous disruption.

The average doses from igneous activity calculated in this manner incorporate uncertainties regarding the time at which the igneous event could occur, and account for the reality that, as time passed, the likelihood would increase that igneous disruptions could have already occurred. For example, a person living downwind from Yucca Mountain 10,000 years after repository closure would have a mean probability of 1.6×10^{-4} of receiving a radiation dose from soil contaminated by an igneous event sometime in the past. The probability-weighted average dose emphasizes the overall risk to a person living downwind from Yucca Mountain, in terms of both the likelihood and consequences of the igneous activity scenario.

Figure 5-7 shows the mean probability-weighted dose histories representing possible doses to an individual for the higher-temperature repository operating mode. The figure also shows the nominal scenario for comparison. The igneous activity scenario is only simulated to 100,000 years because the nominal scenario impacts dominate after that time. These summary curves are based on 5,000 individual dose histories calculated using different sets of uncertain input parameters in the model. For approximately the first 20,000 years, the dose history is a smooth curve that is dominated by the effects of volcanic eruption. The probability-weighted mean annual individual dose during this period would reach a peak of approximately 0.1 millirem about 300 years after repository closure, and then decline because of radioactive decay of the relatively shorter-lived radionuclides that contributed to doses from the ash fall exposure pathway. The major contributors to the eruptive dose would be americium-241, plutonium-238, plutonium-239, and plutonium-240. Strontium-90 would be a significant contributor at extremely early times, but would drop off rapidly because of radioactive decay (*half-life* of 29.1 years). Inhalation of resuspended particles in the ash layer would be the primary exposure pathway during this period, and the smooth decline of the mean dose curve from approximately 300 to 2,000 years would result from decay of americium-241 (half-life of 432 years). From approximately 20,000 years after closure, the mean igneous dose would be dominated by groundwater releases from packages damaged by igneous intrusions that did not erupt to the surface. The irregular shape of the curve from this point forward is in part a result of the groundwater transport processes, and in part reflects the occurrence of intrusive events at random times, rather than the prescribed intervals used for extrusive simulations. The intrusive event could occur at any time, and the first appearance of groundwater doses in the mean curve at approximately 20,000 years reflects retardation during transport, rather than the absence of intrusions at earlier times. Results for the lower-temperature operating mode would be essentially identical to those for the higher-temperature mode because the probability of an igneous intrusion interacting with waste packages is reduced for the wider waste package spacing. However, the overall probability of an igneous intrusion intersecting the potential repository would increase because of a larger repository emplacement area.

The dose history for the igneous activity scenario in Figure 5-7 is presented as a probability-weighted annual dose resulting from events occurring at uncertain times throughout the period of simulation. This approach to calculating and displaying the probability-weighted annual doses is consistent with the approach specified by 40 CFR Part 197 and is required for determination of the overall expected annual dose. However, displays of the probability-weighted annual dose do not allow direct interpretation of the conditional annual dose, which is the annual dose an individual would receive if a volcanic event occurred at a specified time. For conditional analyses, the probability of the event is set equal to one, and the time of the event is specified. Conditional results do not provide a meaningful estimate of the overall risk associated with igneous activity at Yucca Mountain, but they provide insights into the magnitude of possible consequences for specific sets of assumptions. A sensitivity calculation was performed to provide results for this conditional case (DIRS 154659-BSC 2001, pp. 3-47 to 3-48). Conditional mean annual dose histories were calculated for eruptive events at 100, 500, 1,000, and 5,000 years. The conditional mean dose in the first year after an eruptive event at 100 years after repository closure is approximately 13 rem. The conditional dose in the first year after an eruption decreases to approximately one-half this level for an eruption 500 years after closure, and is approximately 10 percent of this value for an eruption 5,000 years after closure. This calculation was made with a previous TSPA model (DIRS 153246-CRWMS M&O 2000, all) that has some differences from the model used elsewhere in this EIS for long-term performance (DIRS 157307-BSC 2001, Enclosure 1). The differences that affect the analysis described above are that dose factors were revised to conform to 40 CFR Part 197 and the

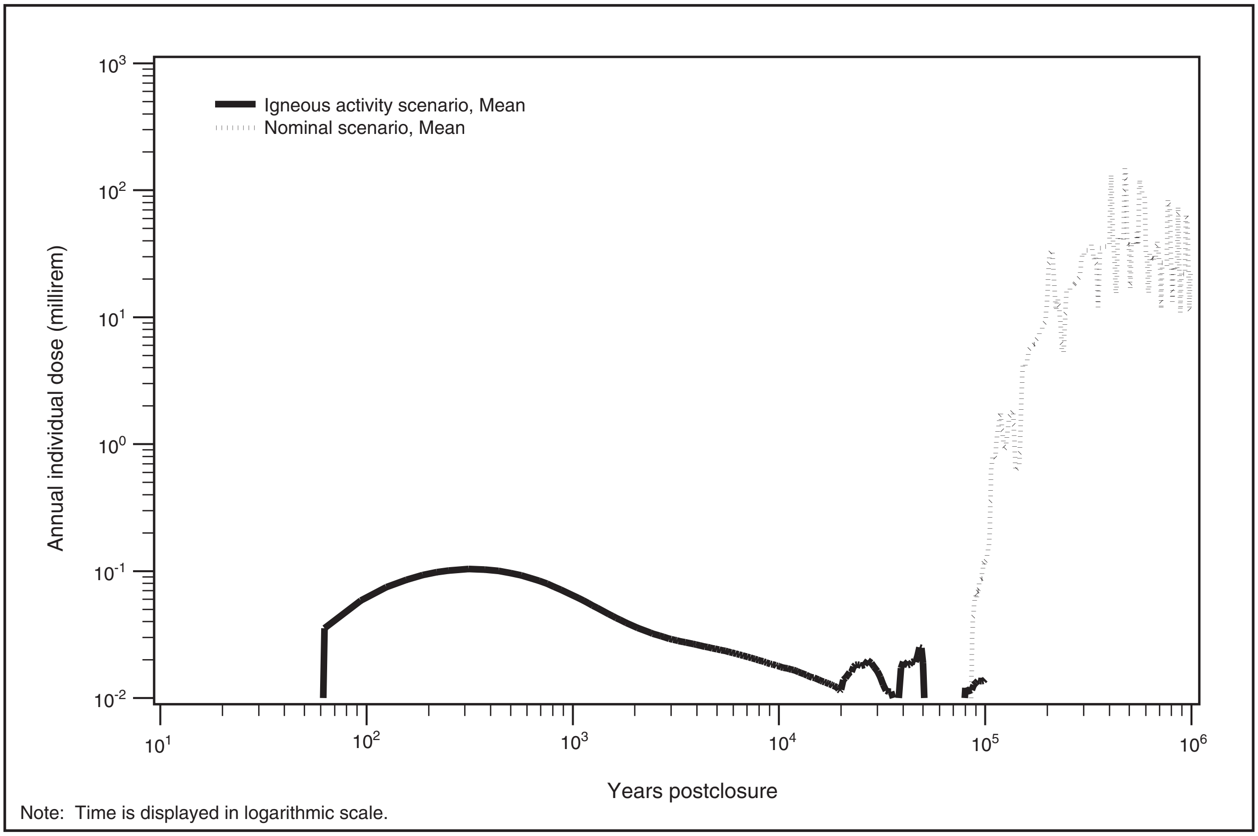

Figure 5-7. Mean (based on 5,000 simulations of total system performance, each using random samples of uncertain parameters) annual individual dose at the RMEI location resulting from igneous disruptions under the higher-temperature repository operating mode, with the mean dose history at this location for the higher-temperature operating mode nominal scenario.

distance analyzed is 20 kilometers rather than 18 kilometers from the repository. These changes would be expected to increase the dose values at 100 years and 500 years by a factor of between 2 and 3. The results at the later times would increase by about 20 percent.

5.8 Nuclear Criticality

This section examines the probability of isolated nuclear criticality events in waste packages and in surrounding rock. A short tutorial on the physics of nuclear criticality and the associated conditions that can cause such an event is provided in the Science and Engineering Report (DIRS 153849-DOE 2001, pp. 4-406 to 4-409). The tutorial provided in the Science and Engineering Report identifies the required conditions for nuclear criticality at the proposed repository. One of the required conditions for nuclear criticality is the presence of a moderator such as liquid water. Liquid water could only be introduced into the waste package if the waste package failed. The following information is excerpted from the Yucca Mountain Science and Engineering Report (DIRS 153849-DOE 2001, pp. 4-412 to 4-416).

5.8.1 PROBABILITY OF INTERNAL CRITICALITY FOR COMMERCIAL SPENT NUCLEAR FUEL

Actually, there is a very low probability that any liquid water would enter a specific package; thus, the probability estimated here is very conservative. Each package would contain a neutron absorber that would have the important function of capturing neutrons and helping to prevent a criticality. The conditions of waste package failure and entrance of liquid water are required for internal criticality. The probability of these conditions occurring would be very small. The probability of the loss of neutron absorber would increase with time after 10,000 years. As the internal components of a waste package degraded, the assemblies in the package would collapses reducing the spacing between the fuel rods. This would reduce the probability of criticality because of the reduced volume between fuel rods available for the moderator to fill. Another factor tending to reduce the probability of criticality with time would be the eventual breach of the bottom of the waste package, which would drain most of the water in the waste package that acted as a moderator. The potential for criticality of commercial spent nuclear fuel would be maximized when the internal basket was fully degraded, but with the assemblies remaining intact and no breach of the bottom of the waste package. Under these circumstances, the calculated probability of a critical event within the total inventory of the 21-PWR Absorber Plate waste packages would be less than 2×10^{-7} in 10,000 years (after closure of the repository). The 21-PWR Absorber Plate waste package was chosen for criticality calculations because it is the design for fuel with the highest reactivity and thus would be expected to have the highest probability of criticality.

5.8.2 PROBABILITY OF INTERNAL CRITICALITY FOR CODISPOSED DOE SPENT NUCLEAR FUEL AND HIGH-LEVEL RADIOACTIVE WASTE

Actually, there is a very low probability that any liquid water would enter a specific package; thus, the probability estimated here is very conservative. Evaluations have been performed of the criticality potential of waste packages that would contain high-level radioactive waste glass and certain types of codisposed DOE spent nuclear fuel. The probability of criticality for these fuel types would generally be less than the small value of 2×10^{-7} for commercial spent nuclear fuel. The primary reasons are the lower fissile loading per waste package and the greater flexibility to install neutron absorber due to smaller fuel mass per waste package.

5.8.3 PROBABILITY OF CRITICALITY FOR THE IMMOBILIZED PLUTONIUM WASTE FORM

Actually, there is a very low probability that any liquid water would enter a specific package; thus, the probability estimated here is very conservative. The design of the immobilized plutonium waste form makes criticality virtually impossible. The degradation rate of the ceramic waste form would be so slow that, in the unlikely event that the waste package was breached and filled by a continuous dripping of water, it would be nearly 50,000 years after emplacement before enough of this waste form had degraded to permit any significant separation of the uranium and plutonium from the gadolinium and hafnium neutron absorbers. Even after degradation of the waste form, the gadolinium and hafnium are generally less soluble than the fissile material, so they would not be transported out of the waste package while the fissile material remains. Even if extremely unlikely chemistry conditions occurred that would make the gadolinium sufficiently soluble to be removed before the fissile material, enough of the completely insoluble hafnium would remain to prevent criticality.

5.8.4 PROBABILITY OF EXTERNAL CRITICALITY

Calculation of the probability of external criticality starts with the assumption that the waste package fails and liquid water has entered the waste package. Actually, there is a very low probability that any liquid water would enter a specific package; thus, the probability estimated here is very conservative. The probability of an external criticality event in either the repository or the rock beneath it is less than 4×10^{-12} in 10,000 years following repository closure. This low probability is primarily a result of the following Yucca Mountain characteristics: (1) limited dripping water to transport enough fissile material out of the waste package and into a geometry favorable for criticality; (2) a limited number of regions in the rock below the drifts to allow for fissile material accumulation in a geometry favorable for criticality; (3) a low concentration of fissile material in the water exiting out of a breached waste package due to low waste form solubility; and (4) lack of a chemical means to accumulate fissile materials and lack of a reducing environment to encourage precipitation.

5.8.5 EFFECT OF A STEADY-STATE CRITICALITY ON RADIONUCLIDE INVENTORY

If a steady-state criticality was to occur, it would be very unlikely to have a power level greater than 5 kilowatts. The power level would be limited because higher power, and thus higher temperatures, would evaporate the water that served as a moderator. An extremely conservative assumption would be that the criticality could endure for 10,000 years, which is the average period of a climate cycle that might have a high enough rainfall or drip rate to sustain the required level of water moderation against evaporation. For a typical commercial spent nuclear fuel waste package, a steady-state criticality would result in an increase of the inventory of certain radionuclides in that waste package. For the very conservative duration of 10,000 years, this increase would be less than 30 percent for the radionuclides in that package. The incremental impact of steady-state criticality events on the total inventory for the repository has been evaluated and is expected to be insignificant.

5.8.6 TRANSIENT CRITICALITY CONSEQUENCES

In the unlikely event that a transient criticality were to occur, a rapid initiating event could produce a peak power level of up to 10 megawatts for less than 60 seconds. After this brief period, rapid boiling of the water moderator would shut down the criticality. The short duration would limit the increase in radionuclide inventory to a factor of 100,000 smaller than that generated by the 10,000-year steady-state criticality. Other consequences of a transient criticality would be a peak temperature of 233ºC (451ºF) and a peak overpressure of 20 atmospheres. Both conditions would last 10 seconds or less and would not be expected to cause enough damage to the waste package or change its environment enough to have a significant impact on repository performance.

5.8.7 AUTOCATALYTIC CRITICALITY

When a criticality begins, there are several mechanisms that tend to shut it down. For example, the rapid evolution of heat and pressure can expand the fissile material, reducing its density and destroying the critical mass configuration. Evolution of steam can remove water moderator or decrease its effective density. In the case of autocatalytic criticality, there is such a high concentration of fissile material that there is an excess of critical mass and high rates of fission are achieved before any of the shutdown mechanisms occur. The result can be a “runaway” chain reaction, usually resulting in a steam explosion, or in the case of a nuclear bomb, a nuclear explosion. Contrary to popular belief, achieving such a configuration is extremely difficult and requires some very deliberate engineering. An autocatalytic criticality is not credible for the potential repository. Autocatalytic criticality is not possible at all for low-enriched waste forms, nor is it possible for the waste form inside the waste package. Even for highly enriched waste forms, or those containing nearly pure plutonium-239, achieving a critical mass outside a waste package would require the entire fissile content of the waste package to be spread uniformly in a nearly spherical shape, or it would require the extremely unlikely commingling of large amounts of transported fissile material from at least two waste packages containing highly enriched waste forms. Because the igneous rock at Yucca Mountain is unlikely to contain deposits that can efficiently accumulate fissile material, the probability of creating such a critical mass from a single or multiple waste packages containing highly enriched waste forms is so low as to be not credible.

5.8.8 DISRUPTIVE NATURAL EVENTS INFLUENCING CRITICALITY

The potential impact of disruptive natural events, such as seismic activity or igneous intrusion, on the risk of criticality in the repository has been studied. Seismic events could produce a rapid change in the configurations of waste forms and waste packages, potentially creating a critical configuration.

The potential adverse criticality considerations of igneous intrusion into the repository include: (1) the possibility of immediate waste package breach, (2) the separation of a significant fraction of the fissile material from the neutron absorber by magma transport, and (3) the accumulation of a critical mass of fissile material from, or within, the transporting magma. The potential for criticality following igneous intrusion has been evaluated for commercial spent nuclear fuel under extremely conservative assumptions, and no sufficiently probable mechanism for accumulating a critical mass has been identified.

5.9 Consequences to Biological Resources and Soils

DOE has considered whether the proposed repository would affect biological resources in the Yucca Mountain vicinity after closure through heating of the ground surface and through radiation exposure as the result of waste migration through groundwater to discharge points. No additional analyses for biological resources and soil have been performed for the design and operating mode changes made after the Draft EIS was published. The temperatures for the higher-temperature operating mode now being considered are bounded by the temperatures analyzed for the high-thermal load scenario in the Draft EIS and presented in this section.

After closure, heat from the radioactive decay of the waste could cause temperatures in the rock near the waste packages to rise above the boiling point of water at this altitude [96°C (205°F)] (DIRS 101779-DOE 1998, Volume 3, p. 3-36). The period the subsurface temperature could remain above the boiling point would vary from a few hundred years to a few thousand years, depending on the operating mode. Conduction and the flow of heated air and water through the rock (advection) would carry the heat from the waste packages through the rock to the surface and to the aquifer.

Although the atmosphere would remove excess heat when it reached the ground surface, the temperature of near-surface soils probably would increase slightly. Predicted increases in surface soil temperatures range from approximately 10°C (18°F) at the bedrock-soil interface (DIRS 100627-Bodvarsson and Bandurraga 1996, p. 510) to 6°C (10.8°F) for dry soil at a depth of 2 meters (6.6 feet) (Table 5-15). To address soil heterogeneity (differences in depth and water content), a recent study (DIRS 103618-CRWMS M&O 1999, all) modeled soil temperature increases at various depths under wet (saturated) and dry (no water at all) soil conditions for the high thermal load. They predicted that temperatures of near-surface soils would be unlikely to rise more than a few degrees (Table 5-14) but would increase with depth from the surface. Surface soil temperatures would start to increase approximately 200 years after repository closure and would peak more than 1,000 years after repository closure. Later, the temperature would gradually decline and would approximate prerepository conditions after 10,000 years (DIRS 103618-CRWMS M&O 1999, Figure 30 and p. 41).

Table 5-15. Predicted temperature changes of near-surface soils under the high thermal load scenario.[a,b]

Soil depth (meters)[c]	Predicted temperature increase [a]	
	Dry soil	Wet soil
0.5	1.5°C (2.7°F)	0.2°C (0.36°F)
1.0	3.0°C (5.4°F)	0.4°C (0.72°F)
2.0	6.0°C (10.8°F)	0.8°C (1.4°F)

a. Source: DIRS 103618-CRWMS M&O (1999, p. 38).
b. The high thermal load scenario was described and analyzed in the Draft EIS; this is not to be confused with the higher-temperature operating mode discussed in this Final EIS, which has a lower design heat loading.
c. To convert meters to inches, multiply by 39.37.

The maximum change in temperature would occur directly above the repository, affecting approximately 5 square kilometers (1,250 acres) under the higher-temperature operating mode. The effects of repository heat on the surface soil temperatures would gradually decline with distance from the repository (DIRS 103618-CRWMS M&O 1999, p. 43). Although not modeled, the increase in surface soil temperature would be lower under the lower-temperature operating mode, and the area that could be affected would be larger [as much as 6.2 square kilometers (1,550 acres) above the repository for the lower-temperature operating mode].

There is considerable uncertainty in the estimates of soil temperature increases due to uncertainties in the thermal properties of the soil at Yucca Mountain, particularly thermal conductivity (the amount of heat that can be conducted through a unit of soil per unit time) (DIRS 103618-CRWMS M&O 1999, p. 50). The predicted temperature increase for dry soil provides a conservative estimate of the temperature increase that could occur because even partially saturated soil has a much greater thermal conductivity than dry soil. Soil moisture content recorded at a depth of 15 centimeters (6 inches) was as low as 3 percent on some study sites during some months, but the soil was never completely dry (DIRS 105031-CRWMS M&O 1999, p. 14).

A depth of 1 meter (3.3 feet) is within the root zone for many desert shrubs. A temperature increase of 3°C (5.4°F) could affect root growth and other soil parameters such as the growth of microbes or nutrient availability. Studies at Yucca Mountain (DIRS 105031-CRWMS M&O 1999, pp. 11 to 46) show that due to natural variations some plant species experienced a spatial range in soil temperatures of 4°C (7.2°F) at a depth of 0.45 meter (18 inches), which is comparable to the 0.5-meter (20-inch) depth used by DIRS 103618-CRWMS M&O (1999, pp. 37-41). Impacts to biological resources probably would consist of an increase of heat-tolerant species over the repository and a decrease of less tolerant species. In general, areas affected by repository heating could experience a loss of shrub species and an increase in annual species. A gradual (over 1,000 years) temperature increase of the magnitude predicted (DIRS 103618-CRWMS M&O 1999, all) probably would have less effect on the plant community than a more rapid change.

The predicted increase in temperature would extend as far as 500 meters (1,600 feet) beyond the edge of the repository, with the greatest increase in temperature occurring in soils directly above the repository. A shift in the plant species composition, if any, would be limited to the area within 500 meters of the repository footprint [that is, as much as 8 square kilometers (2,000 acres)].

A shift in the plant community probably would lead to localized changes in the animal community that depends on it for food and shelter. Specific plant and animal species and community changes cannot be predicted with certainty because changes in climate or seasonal episodic events (droughts, high rainfall) can substantially change species responses to single factors. However, the variation in surface soil temperatures at Yucca Mountain that are caused by elevation, slope, aspect, and other natural attributes suggest that soil temperature increases of the magnitude predicted (DIRS 103618-CRWMS M&O 1999, pp. 44 to 48) are probably within the adaptive range of some plant species now at Yucca Mountain (DIRS 105031-CWRMS M&O 1999, pp. 11 to 46).

Some reptiles, including the desert tortoise, exhibit temperature-dependent sex determination (DIRS 103463-Spotila et al. 1994, all). Nest temperatures have a direct effect on sex determination, with low temperatures resulting in predominately male hatchlings and high temperatures resulting in predominately females. Although existing experimental data do not adequately represent the large fluctuations in nest temperatures in natural settings, an increase in soil temperature due to repository operations could influence the sex ratio and other aspects of the life history of the desert tortoise population residing over the repository footprint. However, depth to the top eggs of 23 nests at Yucca Mountain during 1994 averaged 11 centimeters (4.3 inches). Predicted temperature increases of clutches at that depth based on modeling results (DIRS 103618-CRWMS M&O 1999, pp. 37 to 42) would be less than 0.5ºC (0.9°F). Given the ranges of critical temperatures reported by DIRS 103463-Spotila et al. (1994, all), an increase of this magnitude would be unlikely to cause adverse effects.

Changes in plant nutrient uptake, growth, and species composition, as a result of increases in soil temperature over long periods of time, could influence vegetation community dynamics and possibly alter desert tortoise habitat structure in areas immediately above the repository. However, little is known about the effects that minor alterations in habitat would have on desert tortoise population dynamics.

As discussed in Sections 5.4 and 5.6, in the distant future water at certain discharge points would be likely to carry concentrations of radionuclides and chemically toxic substances. DOE did not quantify impacts to biological resources from irrigation water extracted at the RMEI location, from irrigation water extracted at 30 kilometers (19 miles) downgradient from the potential repository, or for the evaporation of water at Franklin Lake Playa (where there is no surface water at present). The estimated doses to humans exposed to this water would be very small. Expected dose rates to plants and animals would be much less than 100 millirad per day. The International Atomic Energy Agency concluded that chronic dose rates less than 100 millirad per day are unlikely to cause measurable detrimental effects in populations of the more radiosensitive species in terrestrial ecosystems (DIRS 103277-IAEA 1992, p. 53).

The desert tortoise is the only threatened or endangered species in the analyzed repository land withdrawal area (DIRS 104593-CRWMS M&O 1999, p. 3-14). Desert tortoises are rare or absent on or around playas (DIRS 101914-Rautenstrauch and O'Farrell 1998, pp. 407 to 411; DIRS 103160-Bury and Germano 1994, pp. 64 and 65); therefore, DOE anticipates no impacts to this species from contaminated water resources at Franklin Lake Playa in the future.

Impacts to surface soils would be possible. Changes in the plant community as a result of the presence of the repository could lead to an increase in the amount of rainfall runoff and, therefore, an increase in the erosion of surface soils, thereby increasing the sediment load in ephemeral surface water in the immediate Yucca Mountain vicinity.

5.10 Summary

Potential long-term impacts to human health from a repository at Yucca Mountain would be dominated by impacts from radioactive materials in the waterborne pathway under the Proposed Action. Although future disruptive events (human intrusion, volcanic activity, seismic activity) would change radiation exposure rates, the effect of these on the reported impacts for the nominal scenario would be small.

Tables 5-6 and 5-10 list individual doses from groundwater releases of radionuclides during 10,000 years after repository closure. The mean annual individual doses at the RMEI location are summarized in Table 5-16. The mean annual individual doses in Table 5-16 are much less than the limit of 15 millirem in 40 CFR Part 197.

Table 5-16. Individual impacts from groundwater releases of radionuclides during 10,000 years after repository closure for the Proposed Action.[a]

Operating mode	Peak mean annual individual dose at the RMEI location (millirem)[b]	Peak mean annual probability of an LCF[c]
Higher-temperature	0.00002	6×10^{-10}
Lower-temperature	0.00001	4×10^{-10}

a. Values based on the mean peak-dose rates from 300 simulations of total system performance using random samples of uncertain parameters.
b. The RMEI location is approximately 18 kilometers (11 miles) downgradient from the potential repository.
c. LCF = latent cancer fatality.

Tables 5-7 and 5-11 list estimated lifetime and 10,000-year integrated radiation dose impacts for members of the affected population from the groundwater release pathway during the first 10,000 years after repository closure. Table 5-17 summarizes the health effects for the affected population of 74,000 persons based on a 10,000-year integrated basis.

The average mortality rate for cancer deaths per 100,000 persons in Nevada is 202 (DIRS 153066-Murphy 2000, p. 83). Using the Nevada cancer death rate, about 154 cancer fatalities would normally occur each year in the population affected by groundwater potentially contaminated by a repository at Yucca Mountain (74,000 persons). All of the values in Table 5-17 are much smaller than 1, meaning that it is most likely than no person would die due to groundwater contamination by radiological material in the 10,000-year period after repository closure. This comparison clearly indicates that human health impacts associated with effects on groundwater from the Proposed Action would be very small for the affected population. Using the Nevada cancer death rate, about 140 cancer fatalities would normally occur each year in the population within an 80-kilometer radius of Yucca Mountain (assuming a population of about 76,000 persons). All of the values in Table 5-17 are much smaller than 1.0, meaning that it is most likely that no person would die due to groundwater contamination by radiological material in the 10,000-year period after repository closure. This comparison clearly indicates that human health impacts associated with the Proposed Action would be very small for the population in general.

Table 5-17. Population impacts from groundwater releases of radionuclides during 10,000 years after repository closure for the Proposed Action.[a]

Operating mode	Peak annual LCFs[b]	10,000-year integrated LCFs
Higher-temperature	0.000003	0.0002
Lower-temperature	0.000002	0.0002

a. Values based on the mean peak-dose rates from 300 simulations of total system performance using random samples of uncertain parameters.
b. LCFs = latent cancer fatalities.

The analysis indicates (as listed in Table 5-17 and the peak dose values) that there is no significant difference in impacts due to the operating mode, even though the impacts for the higher-temperature mode appear to be slightly larger than those impacts for the lower-temperature mode. One reason for the similarity in annual individual dose between the operating modes is that most waste packages would still be intact beyond the time at which the repository temperature would be elevated much above ambient rock temperatures (DIRS 155950-BSC 2001, p. 7-85). Thus, most radionuclides would not be released until long after the thermal effects had subsided and, therefore, the operating modes would not have a large effect on the peak doses.

The EPA has set annual dose limits of 15 millirem to an individual for human intrusion and igneous disruption events (40 CFR Part 197). As shown in Figure 5-7, the peak of the mean annual dose rate from a human intrusion 30,000 years after repository closure would be 0.002 millirem. The probability weighted mean annual dose to an individual for the igneous intrusion scenario would have a peak of 0.1 millirem. Both of these results are well below the regulatory limits.

The peak mean annual individual doses at the RMEI location in the first 1 million years after repository closure would be 150 millirem for the higher-temperature operating mode and 120 millirem for the lower-temperature operating mode. These doses do not specifically include the effects of disruptive events. The effects of disruptive events would be very small compared to the 1-million-year peak annual dose. These effects are evaluated separately and reported in Section 5.7.

As listed in Table 5-14, human impacts from chemically toxic materials would be unlikely because water concentrations would be below Maximum Contaminant Level Goals (40 CFR 191.51) or Oral Reference Doses (chromium, DIRS 148224-EPA 1999, all; molybdenum, DIRS 148228-EPA 1999, all; nickel, DIRS 148229-EPA 1999, all; and vanadium, DIRS 103705-EPA 1997, all). Estimated concentrations of radionuclides in groundwater (see Table 5-9) would be hundreds of thousands of times less than regulatory limits (40 CFR 197.30). Atmospheric release of carbon-14 would yield an estimated 80-kilometer (50-mile) population impact of 5.3×10^{-10} latent cancer fatality during the 70-year period of maximum release, much lower than the groundwater-borne population impacts. Finally, as discussed in Section 5.9, there are no anticipated adverse impacts to biological resources from either repository heating effects or the migration of radioactive materials.

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Note: In an effort to ensure consistency among Yucca Mountain Project documents, DOE has altered the format of the references and some of the citations in the text in this Final EIS from those in the Draft EIS. The following list contains notes where applicable for references cited differently in the Draft EIS.

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